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Collective, low-lying isoscalar transitions in ^{40}Ca

Ali H Taqi[1], R A Radhi[2*] and A K Ahmed[1]

[1] Department of Physics, College of Science, Saddam University, Baghdad, Iraq

[2] Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

E-mail : sadsci@uruklink.net

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Abstract : The collective, low-lying isoscalar transitions in ^{40}Ca are investigated in the framework of the random phase approximation (RPA). These states include the isoscalar states $J^{\pi}(E_x$ MeV) $3^-(3.74)$, and $5^-(4.48)$. Admixture of higher orbits with the particle-hole pairs already present in the ground state, is taken into consideration. Configurations outside the model space are included, approximately in polarization effective charges. Longitudinal C3 and C5 electron scattering form factors for these states are calculated and compared with the experimental data. Overall agreements are obtained.

Keywords : Isoscalar transitions, collective model, random phase approximation (RPA)

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The theory of collective motion in nuclei can be treated through the theory of random phase approximations (RPA) where the ground state and the excited state are treated more symmetrically, allowing both to have particle-hole pair [1]. In the simple shell model calculation, even-even nuclei are assumed to form closed shells, and excitations from this closed shell are considered to describe the excited states. According to RPA, the ground state as well as excited states are treated on the same footing, and all possible configurations are constructed by removing a particle from the closed shells and promoting it to higher shells leaving a hole state within the closed shells. The ground state and the collective oscillations can be described as a linear combination of particle-hole states. RPA was treated through the relativistic quantum field theory based on a relativistic Hartree approximation (RHA) and applied to the closed shell nuclei such as ^{16}O and ^{40}Ca [2]. In the present work, we use the standard RPA, but allowing the ground state to have admixture of higher configurations than that used for the RPA. We study the collective, low-lying isoscalar transitions in ^{40}Ca. These excitations include the 3^- (3.74 MeV) and 5^{-1} (4.48 MeV) states. The electron scattering form factors for these states are calculated and compared with the available experimental data.

The familiar RPA eigenvalue equation is given by [3]

$$\begin{pmatrix} A & B \\ -B & -A \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix} = E\begin{pmatrix} X \\ Y \end{pmatrix} \tag{1}$$

with

$$A_{1,2}^{JT} = \left(\varepsilon_{p_1} - \varepsilon_{h_1}\right)\delta_{h_1h_2}\delta_{p_1p_2} + \left\langle h_1^{-1}p_1, JT\,|V|\,h_2^{-1}p_2, JT\right\rangle, \tag{2}$$

$$B_{1,2}^{JT} = (-1)^{h_2-p_2}\left\langle h_1^{-1}p_1, JT\,|V|\,p_2^{-1}h_2, JT\right\rangle, \tag{3}$$

where $\varepsilon_{p_1} - \varepsilon_{h_1}$ is the unperturbed energy of the particle-hole pair $p_1h_1^{-1}$.

The two-body matrix element for particle-hole states coupled to angular momentum J and isospin T are given in terms of particle-particle matrix elements coupled to different values J, T [4].

X and Y are the amplitudes for creating a particle-hole pair and for annihilating a particle-hole pair already present in the ground state.

* Corresponding Author

The reduced matrix element of the required electron scattering operator $\hat{T}$ in the spin-isospin spaces, is given by

$$\left\langle \psi_{JT} \left\| \hat{T}_{JT} \right\| 0 \right\rangle = \sum_{p,h} \left| \left\langle h^{-1} p \left\| \hat{T}_{JT} \right\| 0 \right\rangle X_{ph}^{JT} \right.$$

$$+(-1)^{J+T} \left\langle 0 \left\| \hat{T}_{JT} \right\| h^{-1} p \right\rangle Y_{ph}^{J} \tag{4}$$

where the single particle-hole state which is reduced in spin and isospin spaces, is given by the single-particle matrix element reduced in spin only, as [5]

$$\left\langle h^{-1} p \left\| \hat{T}_{JT} \right\| 0 \right\rangle = \sqrt{\frac{2T+1}{2}} \sum_{t_z} I_T(t_z) \left\langle p \left\| \hat{T}_{Jt_z} \right\| h \right\rangle \tag{5}$$

with $$I_T(t_z) = \begin{cases} 1 & for\ T = 0, \\ (-1)^{1/2-t_z} & for\ T = 1, \end{cases} \tag{6}$$

and $t_z = 1/2$ for a proton and $-1/2$ for a neutron.

The single-particle matrix elements of the longitudinal electron scattering operator used in this work are those of Ref. [6].

The form factor of a given multipolarity J and momentum transfer q is given by [5]

$$|F_J(q)|^2 = \frac{4\pi}{Z^2(2J_i+1)} \sum_{T=0,1} \left(\begin{matrix} T_f & T & T_z \\ -T_z & 0 & T_z \end{matrix} \right) \times$$

$$\left\langle \psi_{JT} \left\| \hat{T}_{JT} \right\| 0 \right\rangle F_{c.m}(q) F_{f.s}(q) \tag{7}$$

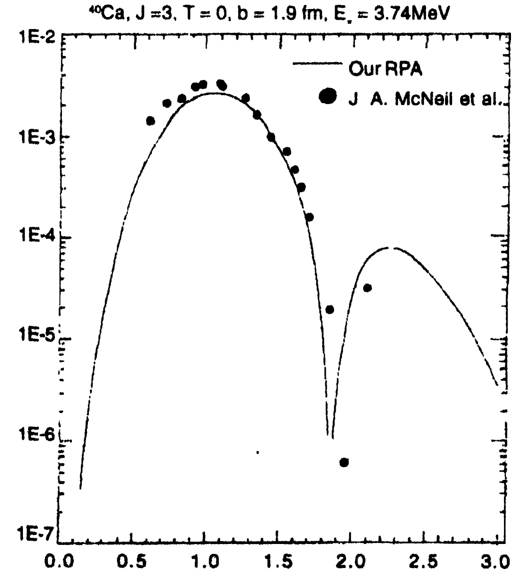

Figure 1. Longitudinal form factor for the 3^- (3.74 MeV) isoscalar state in ^{40}Ca using RPA in comparison with the data of Ref. [8].

where $T_z = (Z-N)/2$. The finite size ($f.s$) nucleon form factor is $F_{f.s}(q) = \exp(-0.43q^2/4)$, and $F_{c.m}(q) = \exp(q^2b^2/4A)$ is the correction for the lack of translational invariance in the shell model. A is the mass number, and b is the harmonic oscillator size parameter.

The orbits in the shells $1s$, $1p$, $2s$-$1d$ and $2p$-$1f$ define the model space used in this work. All possible configurations are obtained by promoting particles from the closed shells $1s$, $1p$, and $2s$-$1d$ to the next $1f$-$2p$ shell. The unperturbed energies $\varepsilon_p - \varepsilon_h$ of the resulting particle-hole (p-h) states are taken from Ref. [7].

The Hamiltonian is diagonalized in the model space in the presence of the modified surface delta interaction (MSDI) [4]. The longitudinal C3 and C5 electron scattering form factors are shown in Figures 1 and 2, respectively. A good agreement with

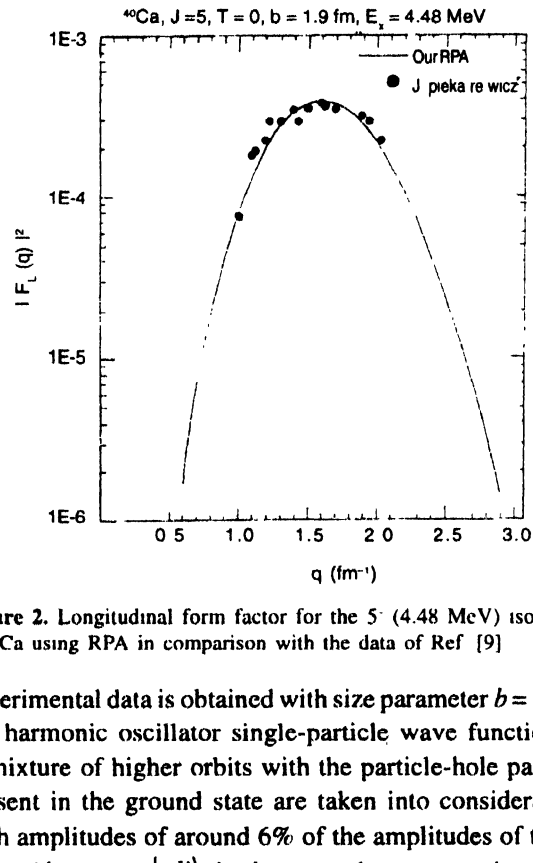

Figure 2. Longitudinal form factor for the 5^- (4.48 MeV) isoscalar state in ^{40}Ca using RPA in comparison with the data of Ref [9]

experimental data is obtained with size parameter $b = 1.9$ fm for the harmonic oscillator single-particle wave functions. Also admixture of higher orbits with the particle-hole pair already present in the ground state are taken into consideration, but with amplitudes of around 6% of the amplitudes of the model space (the states $|nlj\rangle$ in the ground state are mixed with the state $|n+1lj\rangle$). Also, the effective charges are used to compensate for the configurations that are outside the space considered in the work. For the proton and neutron, these effective charges are $e_p = 1.6e$ and $e_n = 0.6e$, respectively, for the 3^- and $e_p = 1.2e$ and $e_n = 0.15e$, for the 5^- states. The data for these states are taken from Refs. [8] and [9], respectively.

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